EXPERIMENTAL STUDIES OF ELECTROSTATIC ACCELERATION OF MICROPROJECTILES

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ABSTRACT

The acceleration of solid material to velocities > 100 km/s using reasonable length accelerators can best be accomplished if electrostatic techniques are utilized. An accelerator for nanogram microprojectiles is being developed to demonstrate the basic principles for a multistage system based on the sequential application of voltage pulses $\geq$ 100 kV. Experiments have been performed stressing carbon material to electric fields > 1.6×10^9 V/m, a field adequate to attain charge-to-mass ratios (q/m) of 5.0 C/kg for micron-diameter projectiles. An injector for charging and launching the microprojectiles into an accelerator has been constructed and operated with q/m = 1 C/kg. Specialized diagnostics for recording the microprojectile's charge and trajectory include a Faraday cup, and a schlieren optical system coupled to an electronic streak camera and to a microchannel-plate framing camera. A five-stage system is presently being and tested to attain a microprojectile velocity of 1 km/s as a proof-of-concept demonstration.

INTRODUCTION

As discussed in the accompanying paper by P.J. Turchi, et al [1], nanogram-masses of solid material (i.e., "microprojectiles") traveling with ultrahypervelocities (> 100 km/s) might be attained with relatively short accelerators by employing electrostatic techniques that can avoid limitations imposed by diffusive processes (e.g., resistive and viscous heating). To achieve such system parameters, projectiles must be charged to levels of ~ 5 C/kg and total effective potentials must be $\geq 5 \times 10^8$ V. Moreover, if the active accelerator length is to be kept to a few tens of meters, the projectile material must possess high tensile strength (>10^9 N/m^2) and have a length of only a few hundred micrometers in order to withstand the accelerator pressure.

As indicated above, the charge that must be transferred to the microprojectile is dependent on its mass. The required charge-to-mass ratio is determined by equating the final microprojectile kinetic energy (1/2 mu^2), to the total effective potential drop of the accelerator column (qV) and solving for q/m:

$$\frac{q}{m} = \frac{u^2}{2V} \tag{1}$$

where m = microprojectile mass, u = final velocity, q = microprojectile charge, and V = effective potential. Transferring sufficient charge to projectile material can only be accomplished by applying very high electric fields at the surface of the microprojectile. For spheres and cylinders, the two most probable shapes for microprojectiles, the relationship among charge-to-mass ratio, the projectile dimensions, and the charging electric field is:

$$\frac{q}{m} = \frac{k\varepsilon_o E_s}{\rho r} \tag{2}$$

where r = microprojectile radius, ε_o = permittivity of free space, E_s = the applied electric field at the microprojectile surface, ρ = microprojectile's mass density, and k = constant = 3 for spheres or 2 for cylinders. If carbon fiber (cylinder with $\rho = 1.8 \times 10^3$ kg/m^3) is chosen as the microprojectile material

because of its high tensile strength (~ 3×10^9 N/m^2) and adequate conductivity, and the projectile radius is 1.0 μm, then to achieve q/m $\geq$ 5 C/kg, $E_s \geq 5.1 \times 10^8$ V/m. This field is comparable to the level at which electron field emission initiates. Therefore, the projectile charge should be positive because the onset of ion field emission does not occur until the field reaches ~ 10^9-10^{10} V/m.

Once a microprojectile has been charged, it must be accelerated through large potentials in order to achieve the desired velocities. Potentials of ~ 500 MV can only be attained through the use of multistage techniques, with the number of stages obviously determined by the voltage per stage. If we select a stage voltage low enough so that we can make use of proven, available components and techniques, for example, voltages in the range of 100-1000 kV, then the total number of stages is in the range of 500-5000. Thus, the microprojectile must be precisely guided through many electrode gaps without drifting or being deflected into an electrode.

This paper presents experimental data that addresses both basic issues: (1) Are high electric fields and charge-to-mass ratios possible with microprojectiles? and (2) Once charged, can such projectiles be accelerated through multistage structures?

MICROPROJECTILE CHARGING

Prior to any experiments with the acceleration of microprojectiles, tests were performed to examine the electric fields that could be applied to carbon fiber material, with particular attention placed on demonstrating q/m values greater than one under vacuum conditions that would be acceptable in the ultimate accelerator. A sketch of the simple, carbon-fiber [2] arrangement is shown in Fig. 1. The brass electrode was pulsed negatively with a double exponential waveform with a 10 μs rise time and a 2.5 ms fall time, causing the center of the fiber to be positively charged. Peak voltages greater than 37 kV were applied to the brass electrode without breakdown. Through the use of a finite element potential plotting code, the field distribution was verified to be that of a coaxial geometry to within ~$\pm$ 5 percent over the 6 mm length at the center of the brass electrode.
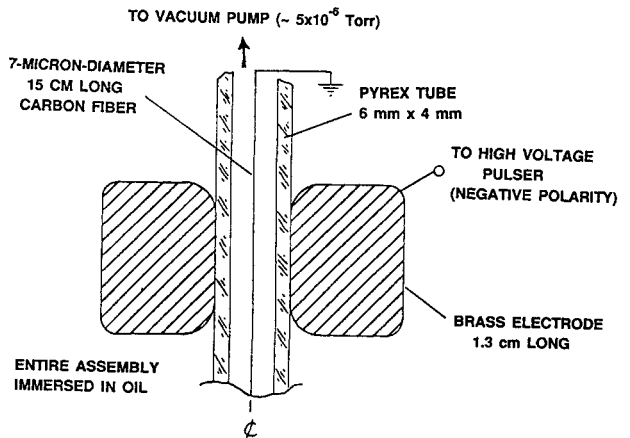

Figure 1. Set-up for charging carbon fibers.

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The acceleration of solid material to velocities > 100 km/s using reasonable length accelerators can best be accomplished if electrostatic techniques are utilized. An accelerator for nanogram microprojectiles is being developed to demonstrate the basic principles for a multistage system based on the sequential application of voltage pulses ~ 100 kV. Experiments have been performed stre~sing carbon material to electric fields > 1.6×10 V/m, a field adequate to attain charge-to-mass ratios (q/m) of 5.0 C/kg for micron-diameter projectiles. An injector for charging and launching the microprojectiles into an accelerator has been constructed and operated with q/m = 1 C/kg. Specialized diagnostics for recording the microprojectile's charge and trajectory include a Faraday cup, and a schlieren optical system coupled to an electronic streak camera and to a microchannelplate framing camera. A five-stage system is presently being and tested to attain a microprojectile velocity of 1 km/s as a proof-of-concept demonstration.

15. SUBJECT TERMS

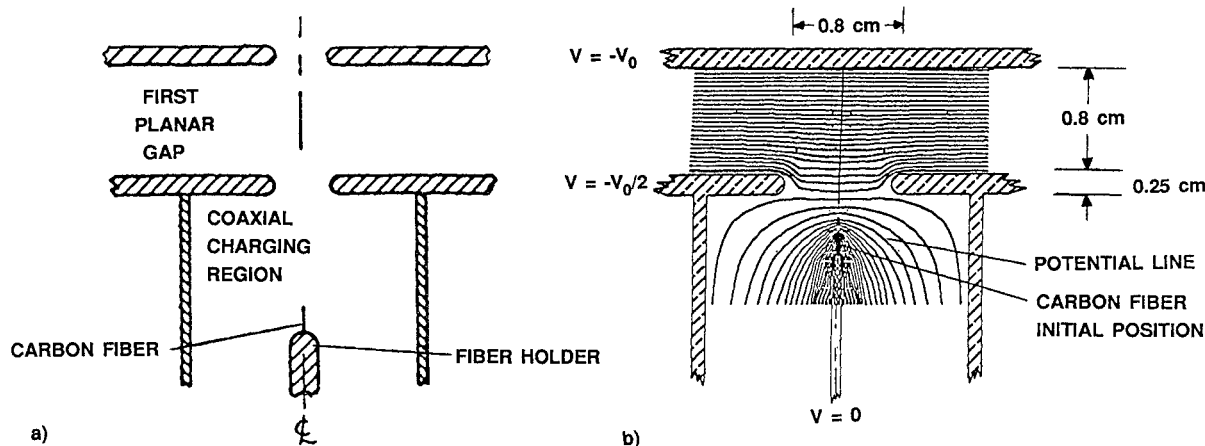| 16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
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Figure 2. a) Geometry for microprojectile charger/injector. b) Equipotential plot for charger/injector.

From the exact analytic solution for an infinite coaxial configuration, the peak electric field at the surface of the fiber at the central region was over 1.6×10^9 V/m. The charge-to-mass ratio corresponding to this electric field is 4.5 C/kg. These results demonstrate that carbon microprojectile material can sustain electric fields that are approximately 10 percent of the ion field emission threshold without breakdown, and that q/m values consistent with the basic requirements for an ultrahypervelocity electrostatic system are possible.

While the preceding experiment illustrates that adequate charge transfer is possible, performing such charging in an accelerator also requires that: (1) charge transfer to a finite length fiber be accomplished with the average charge-to-mass ratio of the entire microprojectile being in the range of a few coulombs per kilogram, and (2) the charging scheme must be able to insert the microprojectile into the accelerator column (i.e., it must be compatible with an injector). To fulfill both of these requirements, the charger/injector shown in Fig. 2a was constructed. The charging/injecting process is initiated simultaneously by applying a high positive voltage to the fiber holder, applying a lower positive voltage to the electrode that forms the outer conductor of the coaxial region and the upstream plate of the planar gap, and by holding the downstream planar electrode at ground potential. The net positive voltage between the fiber holder and the coaxial outer electrode causes a high electric field on the fiber, thus charging it.

The role of the first planar gap is best understood by inspecting the potential distribution of the three electrodes. Figure 2b shows the equipotential plot for the case where the electric field in the planar gap is larger than the electric field between the fiber holder and the exit aperture of the coaxial region. The bulging of the equipotential lines from the planar gap into the cylindrical tube produces an aperture lens [3], i.e., electric field lines emanating from the fiber-holder tip are bent away from the intermediate electrode and directed to the downstream planar electrode. Such an electric field distribution serves to guide the fiber through the aperture. The necessary ratio of electric fields in the two regions is dependent on the geometry. In our experiments, the distance between the fiber tip and the aperture, the aperture diameter, and the spacing of the planar electrodes were comparable; good focusing was obtained when the average electric field in the planar gap was twice the average electric field between the fiber holder and the aperture.

To analyze the overall performance of the charger/injector, two special diagnostics were constructed: (1) a Faraday cup to measure the charge on launched microprojectiles, and (2) a laser-schlieren system that would allow photographic observation of microprojectile trajectories. The Faraday cup system is shown schematically in Fig. 3. A cylindrical copper tube and the intermediate conductor of the triax form the return circuit that defines the capacitance of the Faraday cup. Any charged particle striking the collector charges this capacitance. Figure 4 shows a trace from operation of the injector with +13.5 kV in the charging region and 31.5 kV on the planar gap; the projectile was collected through a hole in the downstream planar electrode. The q/m for the 7 μm-diameter, 5 mm-long fiber was 1.25 C/kg. The
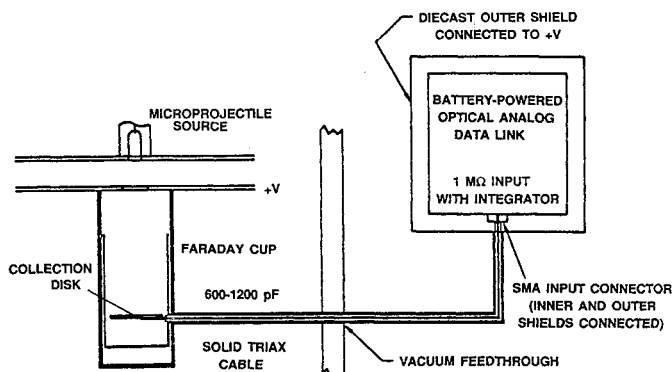

Figure 3. Sketch of the Faraday cup system.
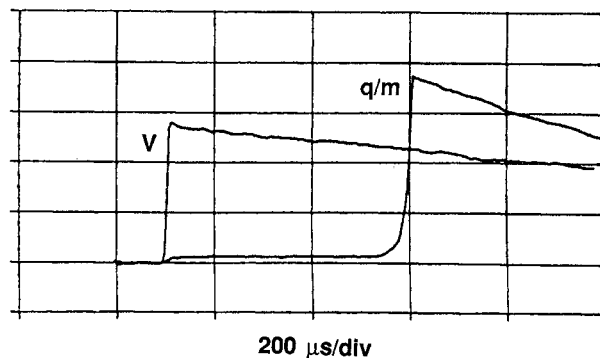

200 μs/div

Figure 4. Digitized data showing the charging voltage waveform (13.5 kV peak) and the signal measured by the Faraday cup at the exit of the first planar gap. The microprojectile q/m was 1.25 C/kg.
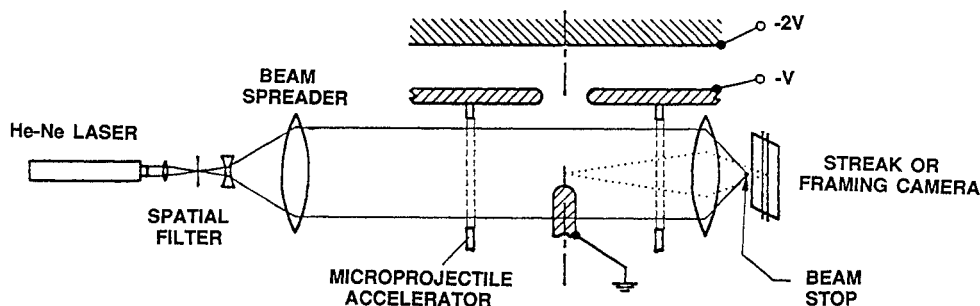
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Figure 5. Schematic diagram of the schlieren system.

leading "foot" on the trace is due to the increasing capacitance between the microprojectile and the collector as the microprojectile approaches.

A schematic diagram of the schlieren system is shown in Fig. 5. Laser light is directed at the fiber holder (through slots in the cylindrical tube) or at the accelerator gaps. Light refracted by the micro-projectile is no longer "parallel" light and is focused beyond the beam stop into either a Hammamatsu electronic streak camera or a gated, microchannelplate camera (RDA design). The streak camera provides some data on the microprojectile trajectory (with resolu-tion limited by the slit width) and a continuous record of the velocity profile. When gated by a short pulse, the microchannel plate camera provides an image of the instantaneous microprojectile orientation; when gated by a long pulse, a complete trajectory is obtained. Rapidly-gated microchannel plate photos have been used to confirm that while most microprojec-tiles are launched at some angle relative to the injector axis, the aperture lensing does "straighten" their trajectories. Figure 6 shows a representative straight trajectory through the planar gap.

MULTISTAGE ACCELERATION EXPERIMENTS

Multistage acceleration of microprojectiles requires integration of the injector with a series arrangement of accelerator gaps. Voltages must be applied to the electrodes in a sequence such that maximum energy is transferred to the projectile while maintaining an electric field distribution that promotes a continued straight trajectory. To examine engineering and physics issues associated with multi-stage operation, a five-stage prototype was construc-ted, as shown in Fig. 7. The charger/injector dis-cussed above launched the microprojectiles, and each downstream electrode was sequentially pulsed by a separate pulser with a timing that matched the dyna-mics of the microprojectile.

Since a goal in the ultimate accelerator is to limit the maximum absolute voltage anywhere in the system to the peak voltage of an individual stage, the accelerator must be operated in a mode where positive

voltages are applied sequentially to the electrode upstream of the microprojectile's position. The voltage must rise with a time much shorter than the transit time through the adjacent downstream gap and must persist for a time equal to the transit time. For the five-stage system operating with a stage voltage of 50-100 kV and a microprojectile q/m of 1 C/kg, transit times range between 20 and 200 μs. The simple circuit ussed to generate such voltages and times is shown in Fig. 8.

To date, experiments have been operated with up to four active stages. The charging potential has been + 13 kV, while the voltage applied to the planar gaps nominally has been + 32 kV. Charge-to-mass ratios have been in the range of 0.6-0.9 C/kg, and the final velocity of the 7 μm-diameter, 5 mm long carbon fiber has been 400 m/s.

These experiments, through the use of the schlieren system and framing camera, have provided significant information on the downstream focusing requirements for maintaining straight trajectories. The preliminary results indicate that the aperture focusing principle applied in the injector design is also adequate for the downstream stages providing the voltage timing is properly synchronized. Recall that as the projectile travels, the voltage of each elec-trode behind the projectile is raised, essentially zeroing the electric field in the gap the micropro-jectile is leaving. The potential difference in the gap into which the projectile is entering is at a maximum and therefore the field there is a maximum. This field bulges through the aperture that the projectile is traversing, producing a focusing effect. Since it is desirable to redirect the microprojectile trajectory before it encounters an electrode aperture, the best focusing effect occurs if the focusing field is established when the microprojectile is a short distance from entering the aperture. This will cause a slight decrease in the overall energy efficiency because the accelerating field is removed before the microprojectile can experience the full potential drop. If the microprojectile passes through the aperture before the voltage is applied, the same bulging of equipotentials that produces focusing at the input aperture now produces a significant defocus-ing effect. Schlieren framing photos showing good focusing as well as significant deflection of a micro-projectile upon passing through an aperture have been obtained.

SCALING TO HYPERVELOCITIES

The five-stage prototype, when operated at the design voltage of 100 kV per stage, will accelerate a microprojectile with q/m = 1 C/kg to a velocity of 1 km/s. If q/m could be raised to 5 C/kg and the stage voltage increased to 200 kV, the final velocity would be 3.16 km/s. Further increase in the charge-to-mass ratio may be possible, but perhaps difficult. Increasing the stage voltage by additional factors up to five is also possible but this approach places a
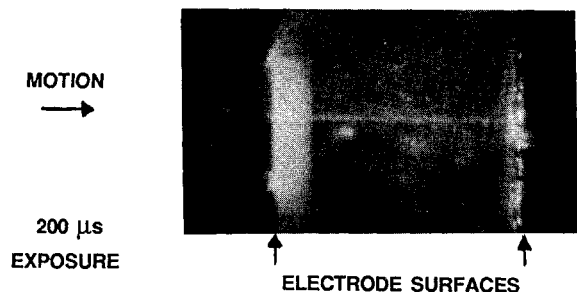
MOTION

200 μs EXPOSURE

ELECTRODE SURFACES

Figure 6. Microchannel-plate camera framing photo showing a straight trajectory through the first stage of a four-stage shot.

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OPEN STRUCTURE   10 cm DIA ELECTRODE   CHARGING REGION   VOLTAGE LEAD   ACRYLIC SUPPORT

ELECTRODE GAP: 2 CM
APERTURE DIA.: 8 MM

FARADAY CUP

ADJUSTABLE SPACERS
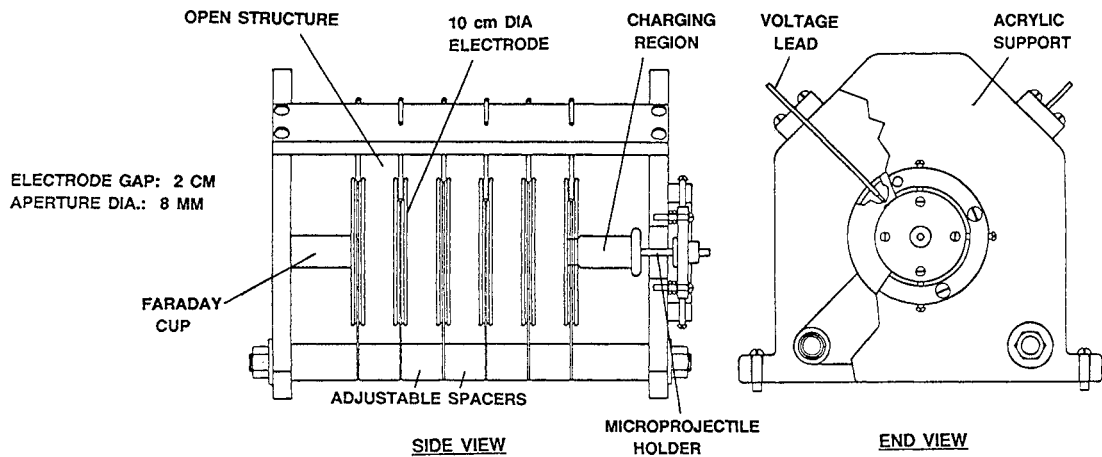
MICROPROJECTILE HOLDER

SIDE VIEW   END VIEW

Figure 7. Sketch of the five-stage prototype used for physics and engineering studies. The flexible design allows for any configuration of one to five stages.

greater burden on the pulsed power, making multistage operation less attractive. Attaining velocities of tens of kilometers per second therefore will require the utilization of a traveling wave voltage source such as the Reflex Transmission Line described by Turchi [1]. However, because the transit time per accelerator gap will vary from approximately 100 μs in the first stages to submicrosecond times at the output stages, a hybrid system may be preferable. For the first few stages, where the transit time changes by a large percentage from stage to stage, discrete pulsers may be the best choice; for intermediate stages, where transit times are in the microsecond range, several traveling wave sources using discrete components can be used. In the fastest stages, a traveling wave scheme that employs the parasitic stage capacitances and inductances as the primary electrical elements of voltage transmission line might be the most efficient.

In order to maintain a compact system at high velocities, the electric field in the accelerating stage should be as high as possible. As discussed in the paper by Tripoli, et al [4], elimination of bare electrode surfaces through the use of encapsulation techniques may result in systems where the high dielectric strengths of some insulating films will allow operation at gap gradients of a few hundred megavolts per meter. Gap lengths would be on the order of a millimeter for 200 kV potentials, a dimension that is consistent with the few hundred micrometer length ultrahypervelocity projectiles would have. In such an extreme, the electrode thickness may dominate the overall system length, although as discussed earlier, thin electrodes ·(~ 1 mm) are probably needed for good aperture focusing. Thus a 100 km/s system might consist of a 2 μm-diameter, 200 μm-long projectile, traveling through 5000 gaps, each pulsed sequentially to 200 kV. At the nominal gap and electrode dimension of 1 mm, the 5000 accelerator stages would result in an accelerator column 10 m long.

TRIGGERED
SPARK
GAP   TO ACCELERATOR
          ELECTRODE
4 mH
                    $V_1 = 1.95 V_0$
18 nF
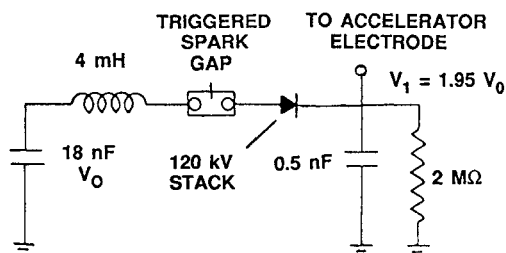V_0 120 kV   0.5 nF
         STACK   2 MΩ

Figure 8. Circuit used to pulse each of the accelerating gaps in the five-stage prototype.

CONCLUSIONS

The experiments reported herein have demonstrated the basic requirements for considering ultrahypervelocity acceleration of projectiles with masses in the nanogram range. The fact that electric fields > 10^9 V/m can be sustained on macroscopic particles is extremely important, as is the demonstrated ability to achieve charge-to-mass ratios > 4.5 C/kg. Equally important is the success in utilizing such charged materials in a multistage system with guided trajectories. Based on the results presented here, launch, on command, of precision microprojectiles traveling at velocities of several kilometers per second to a few tens of kilometers per second is feasible with present multistage electrostatic techniques. To attain ultrahypervelocities the development of advanced traveling voltage wave drivers is necessary. Additionally, issues such as microprojectile charge retention in long systems, maximizing electric field distributions in charging regions in accelerator gaps, and developing more sophisticated microprojectile sources with controlled launch characteristics must be addressed. Future work is planned to examine these technological requirements.

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